

ELECTRONIC FUNDAMENTALS

THEORY LESSON 12

D-C AND A-C GENERATORS

- 12-1. Direction of Current Flow
- 12-2. Induced EMF and Current Flow
- 12-3. Electromagnetic Induction
- 12-4. Graphs
- 12-5. Simple A-C Generator
- 12-6. D-C Generators
- 12-7. Practical Generators
- 12-8. Transformers
- 12-9. Transformer Losses
- 12-10. Transformer Types



RCA INSTITUTES, INC.

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HOME STUDY SCHOOL**

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Theory Lesson 12

INTRODUCTION

From earlier lessons, you know that electricity can be produced by friction. You know that, by means of friction, electrons may be wiped off a material, leaving it positively charged. The body to which the electrons attach themselves then becomes negatively charged. You know that if these two charged bodies are joined by a conductor, current electricity will flow. You also know that this is not a very satisfactory or practical method of producing electricity. You know, too, that electricity may be produced chemically, as in a primary or secondary cell, and that this method of producing electric power is widely used. However, most of the electricity produced for lighting, heating, cooking, operating motors, radios, TV sets, and so forth, is produced by still another method. We call this the electromagnetic method.

In 1831, an English scientist, Michael Faraday, discovered a strange thing. He found that he could produce an electric current in a closed circuit simply by moving the circuit across a magnetic field or by moving a magnet (and magnetic field) across the circuit. Figure 12-1 shows how this may be done. Part *a* shows a single conductor, connected to a sensitive meter, being moved so that it cuts across the lines of force of a magnet. The meter shown is one with the zero calibration line in the center of the scale, so that the direction of the induced current may be indicated. Part *b* of the figure shows another conductor, one of several turns, connected to a sensitive meter. In this case, the conductor is not moving. Instead, the magnet with its magnetic field is being pushed into the coil.

12-1. DIRECTION OF CURRENT FLOW

The direction of the current flow caused by the induced emf is determined by:

1. The direction of flux lines of the magnetic field.

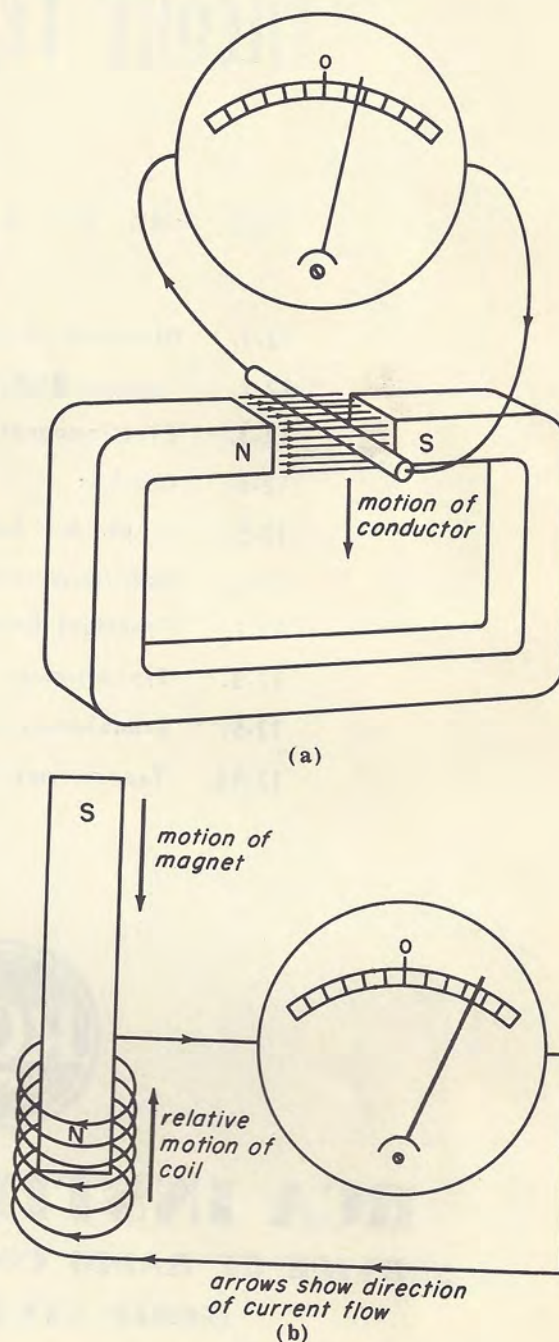


Fig. 12-1

2. The direction of the relative motion between the conductor and the magnetic field.

From your study of magnetism, you know that the direction of the flux (magnetic lines of force) is from the North pole, through the field, to the South pole. When we speak of the relative motion between the conductor and the magnetic field, we mean that it makes no difference which moves, the conductor or the field, because the effect is the same. So, when the relative motion between the conductor and the magnetic lines of force is reversed, as in Fig. 12-2, the direction of current is opposite to that of the first current. Therefore, the current produced when the magnet is thrust in the coil is opposite to the current produced when the magnet is removed from the coil.

Left-Hand Rule For Generators. There is a rule for finding the direction of current flow. We call it the left-hand rule for generators. It goes like this: Hold the thumb, middle finger, and forefinger of your left hand as shown in Fig. 12-3a. If you place them correctly, each finger will be at right angles to the other two. Now, with the fingers still in this position, place your hand over the drawing of Fig. 12-3b. Let your thumb point in the direction of motion of the conductor, and your forefinger point in the direction of the flux lines. Your middle finger will point to the direction in which induced emf; that is the direction in which current flows. Please remember that, in these lessons, current flows in the direc-

tion of the movement of electrons. If you do this correctly, you will find that the current flows toward you, as shown by the dot in the drawing.

12-2. INDUCED EMF AND CURRENT FLOW

Faraday discovered that:

1. A voltage is induced when there is relative motion between the conductor and the magnetic field.

2. A voltage is induced only when the conductor cuts *across* the lines of force, or the lines of force cut *across* the conductor.

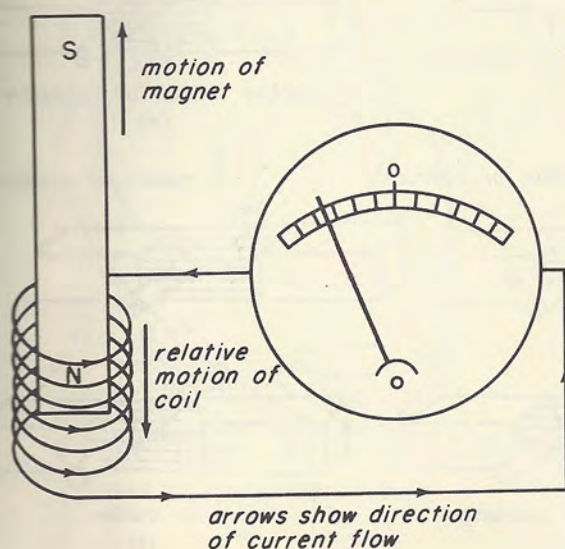


Fig. 12-2

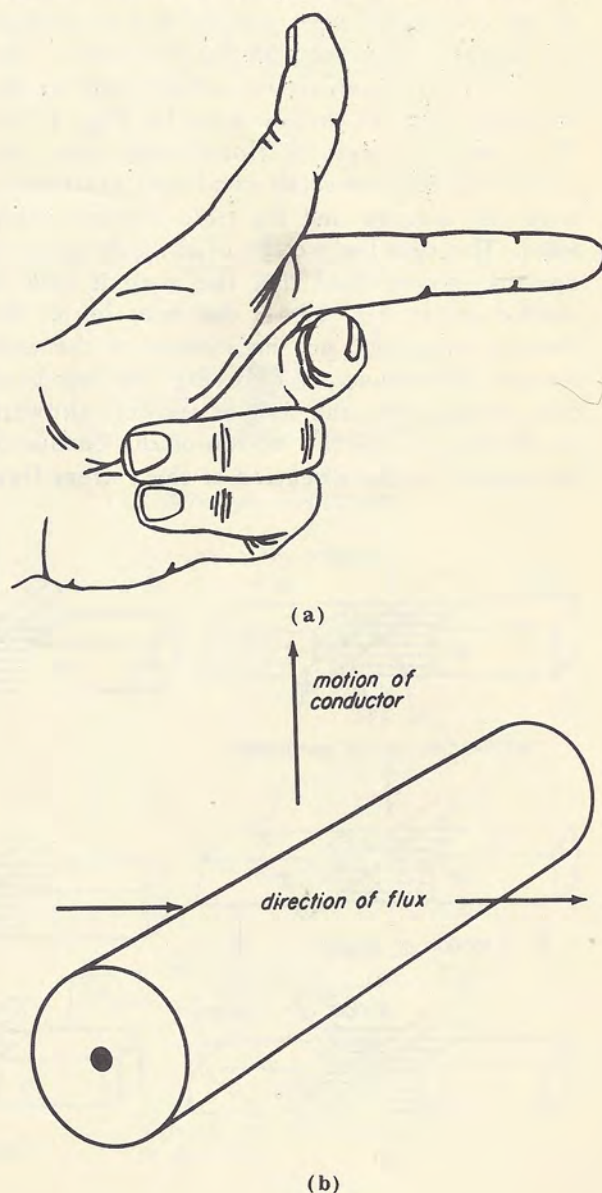


Fig. 12-3

3. The polarity of the induced emf reverses when the direction of relative motion between conductor and magnetic field is reversed.

The drawings in Fig. 12-4 show how these facts affect the flow of current in a conductor placed in a magnetic field. Figure 12-4a shows the conductor moving downward. By applying our left-hand rule, we see that the direction of current flow is away from us. Figure 12-4b shows the motion of the conductor is upward, so that the current now flows toward us. In 12-4c, the conductor is stationary and the magnet with its field moves upward. The relative motion between the magnet and the conductor is, therefore, the same as it would be if the conductor were moving downward with the magnet stationary. So the direction of the relative motion, which we use in applying the left-hand rule, is the same as for Fig. 12-4a. Therefore the current flows away from us. Figure 12-4d shows the conductor stationary, with the magnet and its field moving downward. The relative motion of the conductor is upward, so we find that the current flow is toward us. In Fig. 12-4e, the direction of the flux is reversed, so the motion of the conductor is downward. Applying the left-hand rule, we find that the flow of current is toward us. In Fig. 12-4f, the motion of the conductor is upward, so the direction of the current flow

is away from us. In Parts g and h of the figure, the motion of the conductor is parallel with the direction of the flux lines. The conductor does not cut across any lines of force, and the drawing thus shows that there is no current flow. Figure 12-4i shows no motion, either of the conductor or of the magnet and its magnetic field, so the drawing shows that there is no current flow.

12.3. ELECTROMAGNETIC INDUCTION

The method of producing electricity just described is called *electromagnetic induction*. We say that this method *induces* emf in the coil or conductor and that, as a result of this induced emf, a current flows in the coil or conductor. From your study of magnetism, you know that when magnetism is induced in a piece of magnetic material, it is done by placing the magnetic material in a magnetic field. So, when we say that an emf is induced, we mean that it is produced without electrical contact with the circuit in which it is induced.

The amount of emf produced by electromagnetic induction depends upon the speed with which a conductor cuts across

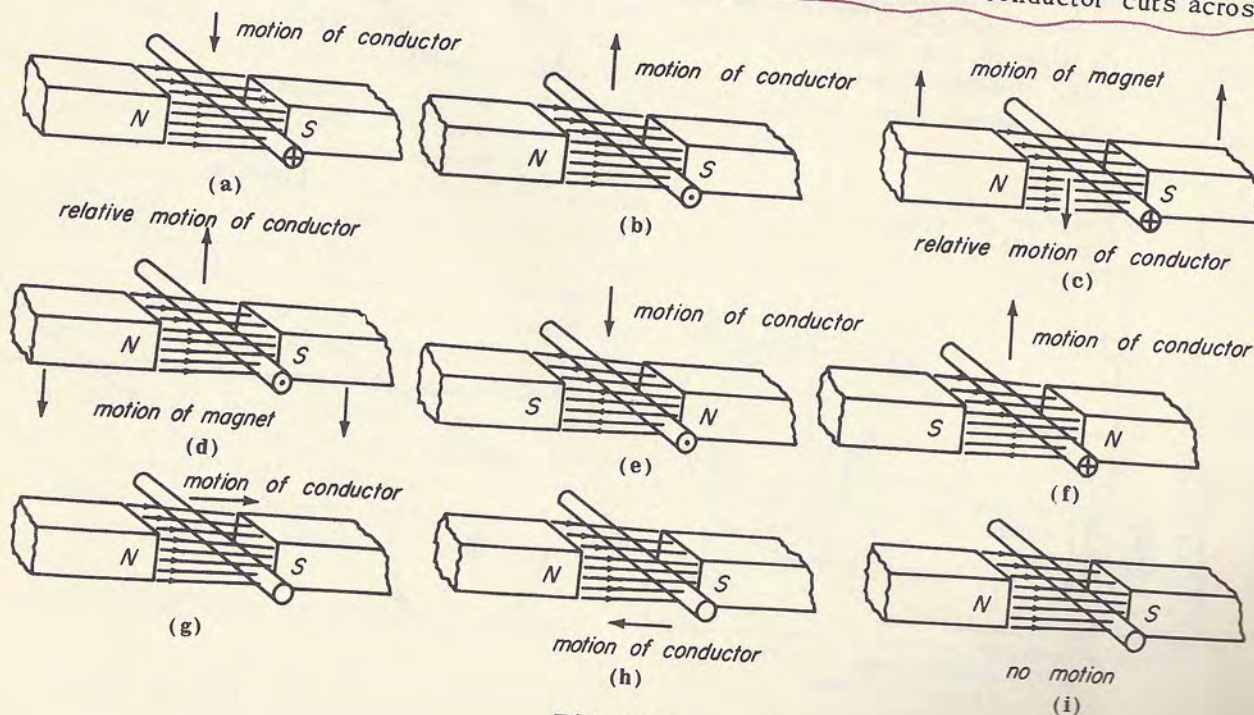


Fig. 12-4

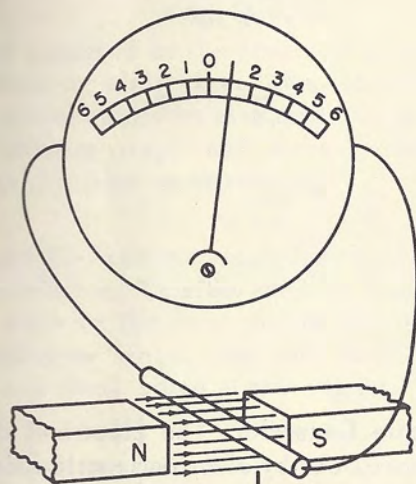
magnetic lines of force. This means that the faster the flux lines cut the conductor or the conductor cuts across the flux lines, the greater is the induced voltage. Therefore, to increase the amount of induced emf, it is necessary to increase the number of flux lines cut per second by the conductor. Practically, we may do this in three ways:

1. By increasing the flux density (increasing the number of lines of force in a given space). This may be done by increasing the magnetic strength (shown in Fig. 12-5a) as is done in Fig. 12-5b.

2. By increasing the speed of the conductor. Doubling the speed of the conductor doubles the induced emf, as shown in Fig. 12-5c.

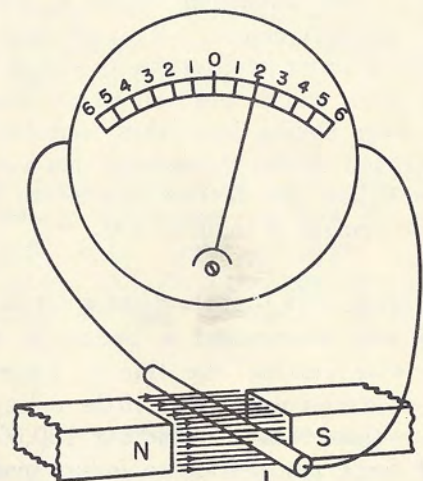
3. By increasing the number of conductors. This may be done by increasing the number of turns in the conductor that cuts the magnetic flux. Doubling the number of turns in the conductor doubles the emf induced, as shown in Fig. 12-5d.

The amount of emf induced in the moving coil of a generator may be found by using the



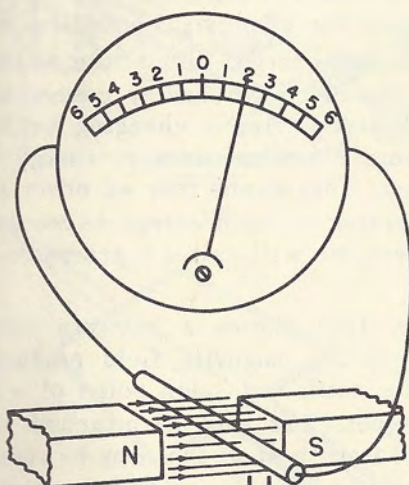
note amount of induced EMF with a certain flux at a certain speed

(a)



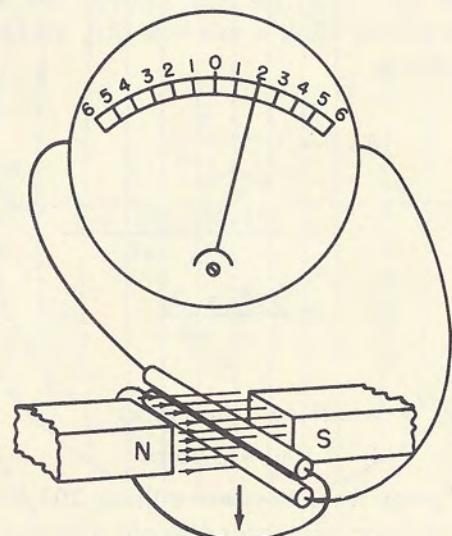
flux density is doubled

(b)



speed of motion is doubled

(c)



number of conductors is doubled

(d)

Fig. 12-5

following formula:

$$Emf = \frac{F \times N}{t \times 10^8}$$

where:

Emf = the average value of the voltage induced in the coil

F = the flux—the total number of lines of force cut by the coil

N = the number of turns in the coil

t = time in seconds

This is not supposed to be a practical formula for servicemen. What is more, you could spend an entire lifetime as a technician, working with radio and television circuits, without ever having seen this formula. It is only included in this lesson so that you may better see how the factors discussed above affect the amount of induced emf.

Let's break this formula down a bit in order that we may understand it better. A single turn of wire cutting one line of force in a second produces very, very little voltage. In fact, one turn of wire must cut 100,000,000 lines of force per second to induce one volt in the wire. A two-turn coil cutting the same number of lines of force in the same time induces two volts. From your study of powers of ten, you know that 100,000,000 may be expressed as 10^8 . Let's see how this works with the formula:

$$\begin{aligned} Emf &= \frac{F \times N}{t \times 10^8} \\ &= \frac{100,000,000 \times 2}{1 \times 10^8} \\ &= \frac{10^8 \times 2}{1 \times 10^8} \end{aligned}$$

The 10^8 's cancel out; therefore:

$$Emf = 2 \text{ volts}$$

In the same way, one turn cutting 200,000,000 lines of force per second would also induce 2 volts. Applying the formula as before:

$$Emf = \frac{F \times N}{t \times 10^8}$$

$$\begin{aligned} &= \frac{200,000,000 \times 1}{1 \times 10^8} \\ &= \frac{2 \times 10^8}{1 \times 10^8} \\ &= 2 \text{ volts} \end{aligned}$$

Let's see what happens when the speed of cutting is increased. Suppose a one-turn conductor cuts 100,000,000 lines of force in one half-second. Then:

$$\begin{aligned} Emf &= \frac{F \times N}{t \times 10^8} \\ &= \frac{10^8 \times 1}{0.5 \times 10^8} \\ &= \frac{1}{0.5} \\ &= 2 \text{ volts} \end{aligned}$$

A Simple Generator. The electrical device that produces emf by electromagnetic induction is called a *generator*. To *generate* means to produce; to cause to be. When we say that we generate electricity with a generator, however, this is not strictly true. We are not producing electricity from nothing. Actually, a generator is a device for changing mechanical energy into electrical energy. Without the mechanical energy, the electrical energy cannot be produced. What is more, in changing mechanical energy into electrical energy, energy is actually lost. This means that we never get out of a generator as much energy as we put into it. However, we still call it a generator.

Figure 12-6 shows a one-turn conductor rotating in the magnetic field produced between the north and south poles of a permanent magnet. The coil is attached to, and insulated from, a shaft that may be rotated by turning the handle. One end of the coil terminates in a copper or bronze ring, marked CR₁. The other end of the conductor terminates in a similar ring marked CR₂. These rings are called *collector rings*, or sometimes *slip rings*. They are called collector rings because

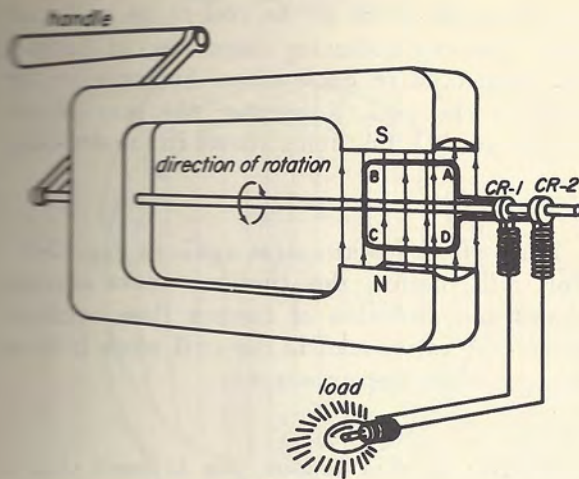


Fig. 12-6

the emf produced by the generator is collected from them by sliding contacts. These sliding contacts are called *brushes*; they press against the collector rings and make contact with them as the drive shaft rotates.

Figure 12-7a shows another view of the one-turn conductor. This is more or less a front view, showing the front end of the shaft, with the collector rings, the coil, and only the north and south poles of the magnet. The coil

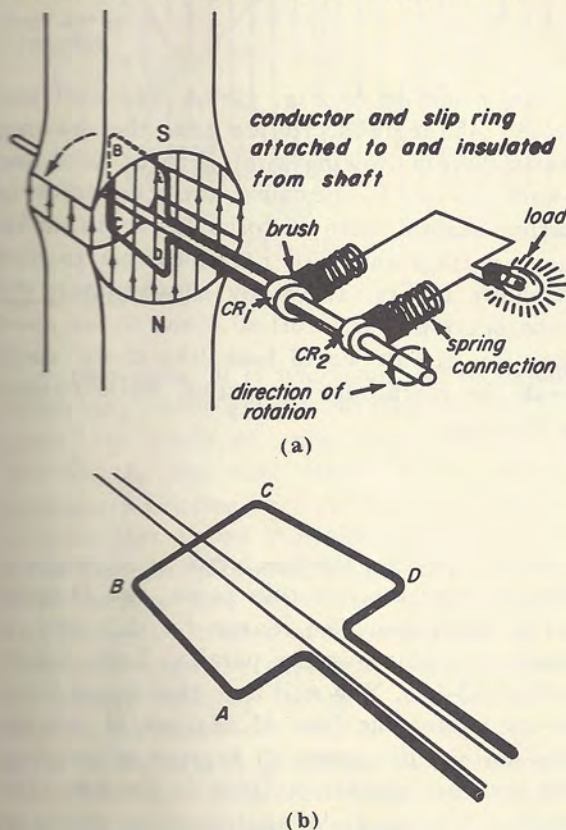


Fig. 12-7

is shown in the same position with respect to the poles as in Fig. 12-6.

Note that the poles are shaped so that the coil may rotate between them without touching them. The arrows indicate that the coil is rotating in a counterclockwise direction. In Fig. 12-7b, the coil has made a quarter rotation and is in a horizontal position.

In order to follow the action of a generator producing electricity, you must concentrate your attention on some very small but important details. So, although the drawings in Fig. 12-6 and 12-7 are fairly simple, we need some even simpler drawings.

One such drawing is 12-8, which shows the coil in the same position as in 12-7b. However, this drawing shows only the two poles, the direction of the flux, the direction of the movement of the coil,

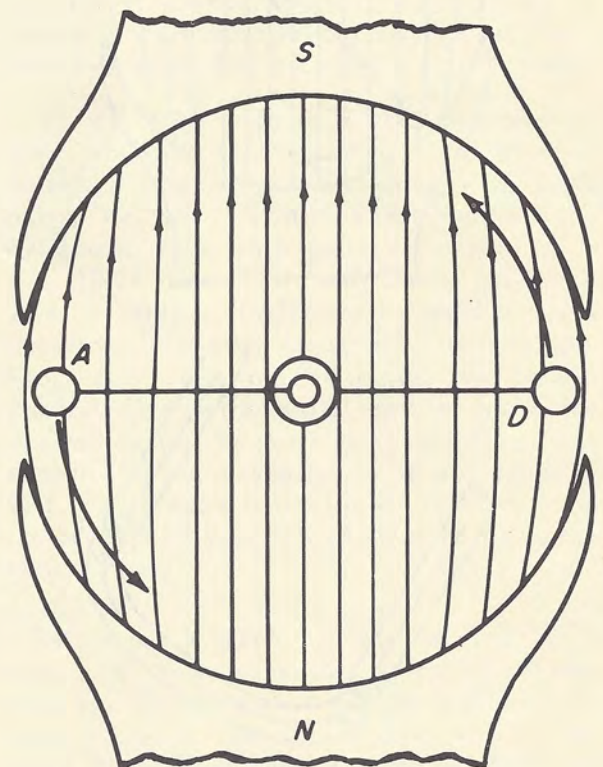


Fig. 12-8

and the coil itself. The coil is represented by two circles connected by straight lines to two more circles. Because we will use this kind of drawing in the explanation that follows, it is important that you know exactly what is meant by these circles and straight lines. The circle marked *A* represents the part of the winding of the coil which is shown going from *A* to *B* in Fig. 12-7b. It is supposed to be a cross section of the wire. The reason a cross-section is shown is so that you may see the direction of current flow inside the coil. The straight line that connects *A* to the smaller of the center circles represents the connection between the *A*-end of the coil and its collector ring. *D* represents the other part of the coil, shown in Fig. 12-7b as running from *C* to *D*, and the straight line connecting it to the larger of the center circles shows the connec-

tion from the *D*-end of the coil to its collector ring. The two collector rings are, of course, not connected to each other, but only to the ends of the coil. Remember the rest of the coil is used; it just isn't shown in the drawing.

Let's direct our attention again to Fig. 12-8. You will notice that neither cross section shows the direction of current flow because no voltage is induced in the coil when it is in this position. Let us see why.

Earlier in this lesson you learned that a voltage is induced when either the conductor moves across the lines of force or the lines of force move across the conductor. When the coil is in the position shown in Fig. 12-8, the arrows show that the coil is moving. However, take a very close look at one end of this coil. For a very short time, the movement of the coil, as shown by the cross section *A*, is parallel with the flux lines. Thus, for this very short time, neither *A* nor *D* is cutting across the lines of flux. And, with no flux lines being cut, there is no induced voltage.

Now move on to Fig. 12-9a. The coil has rotated 45 degrees. Notice that the drawing shows current flowing away from us at *A* and toward us at *D*. Because the conductor is cutting across lines of force, there is an induced voltage that will cause current to flow as shown in Fig. 12-9b. By showing only the cross section of the coil at *A* and *D*, we show what the circuit would look like if we could break the circuit for an instant while current is flowing.

In Fig. 12-10a, the conductor is shown in a vertical position. At this point, the induced emf is maximum. The reason for this may be found by looking at the parallel lines shown in Fig. 12-10b. You will note that fewer lines are cut during the first 45 degrees of rotation than during the second 45 degrees of rotation. The greatest number of lines is cut when the conductor is at right angles to the lines of force.

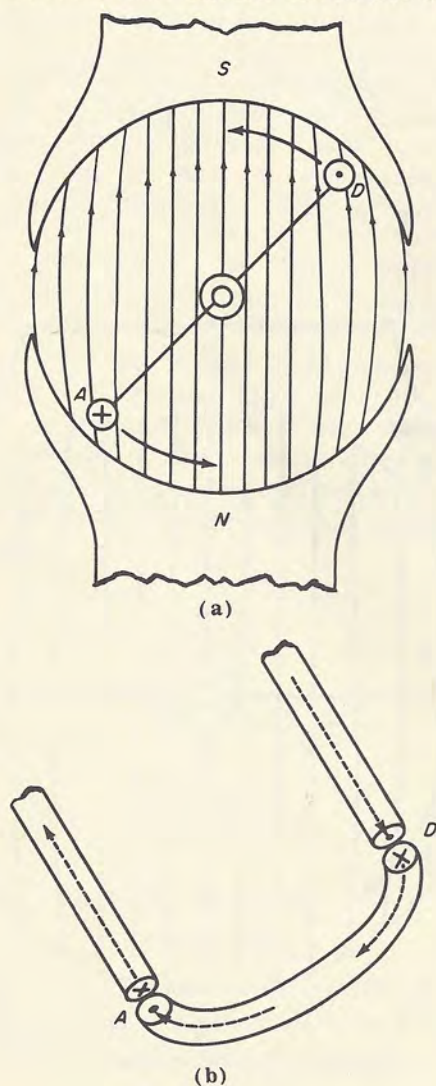


Fig. 12-9

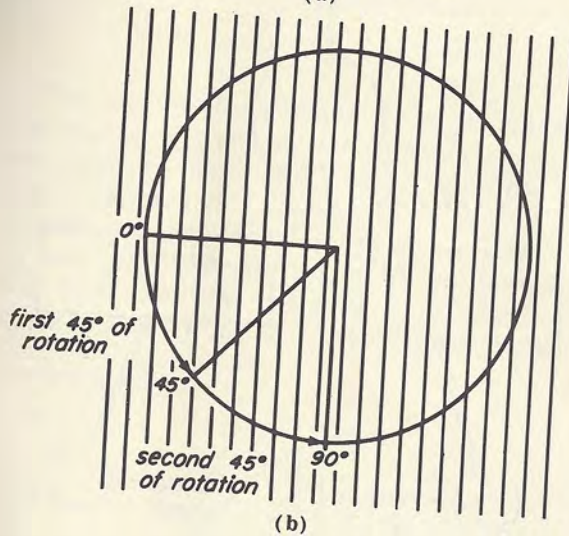
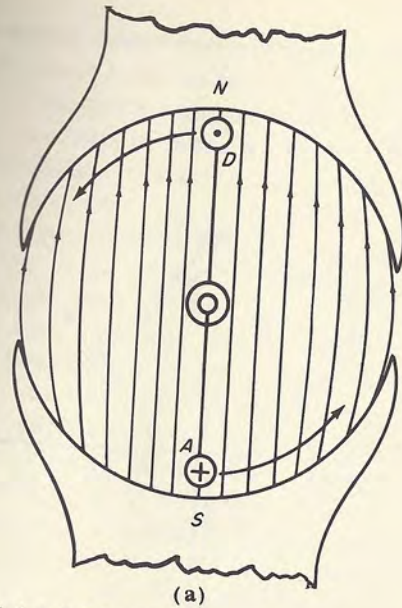


Fig. 12-10

12-4. GRAPHS

At this point, it is necessary for us to know something about *graphs*, so that we may continue our study of generators. Without this knowledge, the next steps in the study of generators become very difficult. A graph is a diagram that shows how one quantity depends on or changes with another quantity. You must have noticed how often drawings, diagrams, and pictures are used in these lessons to help you understand the action of circuits and the parts that make up circuits. A graph is just another diagram—one that takes the place of a lot of figures. A graph usually is easier to understand than a series of figures would be, because the changes in quantities that take place may be seen and understood almost at

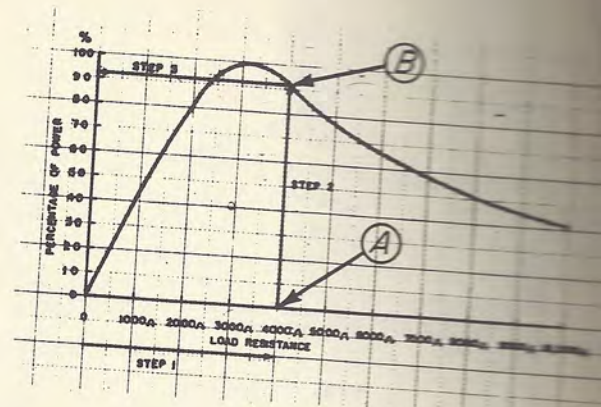


Fig. 12-11

a glance.

One of the most popular kinds of graph is the *line graph*. Figure 12-11 shows such a graph. It shows the relative power output of a battery for different values of load resistance. The power is marked off in percentages on the line that runs up and down, which we call the *vertical axis* or, sometimes, the *Y axis*. The load resistance is marked off in steps of 1,000 ohms on the line that goes across the page, which we call the *horizontal axis* or, sometimes, the *X axis*. The line formed in making this graph is called a *curve*. Such lines are not always curved; in fact, they may be irregular or even straight. No matter what shape they may have, they are always called *curves*.

We use such a graph in this manner. Suppose we want to know how much power is delivered when the load resistance is 4,000 ohms. We first find the 4,000 point on the horizontal axis; this point is marked A in Fig. 12-11. From this point on the horizontal axis, we draw a line vertically until it meets the curve. This point is marked B on the graph. From this point on the curve, we draw a straight line horizontally until it meets the vertical axis. We find that this line falls one-fifth of the way between 90 and 100%, or 92%. So we know that with a 4,000-ohm load, the battery delivers 92% of its maximum power output.

We say of a graph like that in Fig. 12-11 that it is drawn to scale, which means that each unit on either axis is represented by the same length of line as any other unit on the same axis. When such a graph is drawn on graph paper, it is easy to locate points on either axis that lie between those that are

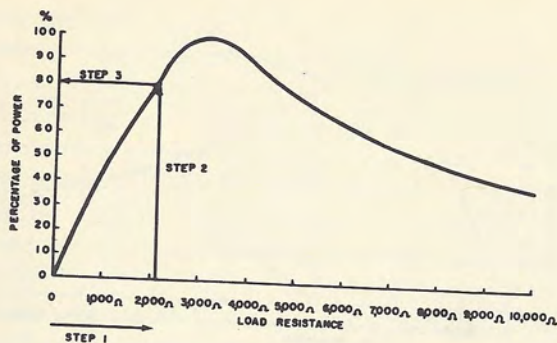


Fig. 12-12

marked off. For example, each line that meets the horizontal axis between the 1,000-ohm points represents a 100-ohm step, and each line that meets the vertical axis represents a 2-percent step.

However, it is not necessary to draw such a graph on graph paper. The same information may be obtained when the graph is drawn as it is in Fig. 12-12. When drawn in this manner, graphs are a little more difficult to read accurately than those drawn on graph paper. Let us suppose that we want to know the relative power output of the battery when the resistance of the load is 2,100 ohms. We first find the 2,000-ohm mark and then continue one-tenth of the distance between this point and the 3,000-ohm mark. From this point, we draw a line perpendicular to the horizontal axis until it meets the curve. From this point on the curve, we draw a horizontal line to the vertical axis. We find that this line meets the vertical axis at the 80-percent point. The power, therefore is 80 percent.

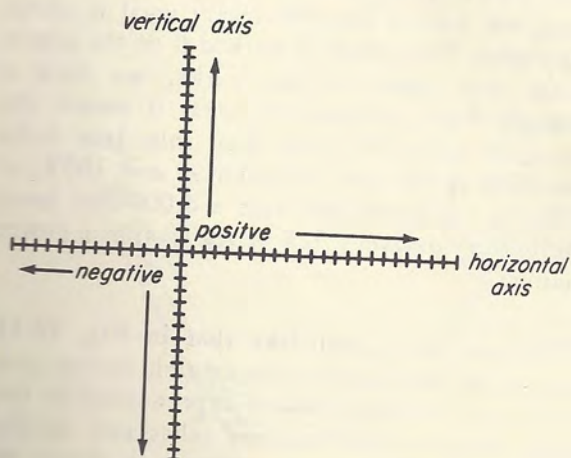


Fig. 12-13

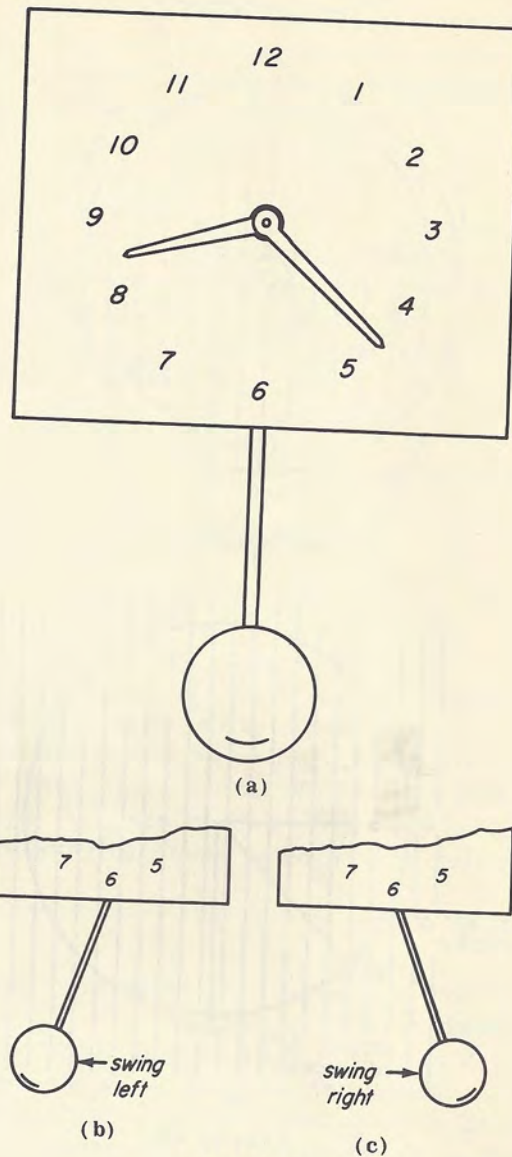


Fig. 12-14

Extending the Axes. The vertical axis may be extended below the horizontal axis, and the horizontal axis may be extended beyond the vertical axis, as shown in Fig. 12-13. The point where the horizontal and vertical axes intersect (come together) is usually considered zero for both axes. Any point on the vertical axis *above* the horizontal axis is considered *positive* in value and direction. Any point on the vertical axis *below* the horizontal axis is considered to be *negative* in value and direction. All values on the horizontal axis to the left of the vertical axis are considered *negative* in value and direction, and those to the right, *positive* in value and direction.

Let us see how such a graph is used to

show values where there is a change in direction. Figure 12-14a shows a clock with a pendulum. The clock has stopped; the pendulum is in a position of rest. When the clock goes, the pendulum swings back and forth at a regular rate. Once in every second, it moves through the position of rest to the left as shown in Fig. 12-14b, returns through the position of rest to the right, as shown in Fig. 12-14c, and back to the position of rest. In each succeeding second, it makes a similar swing to the left and to the right. Figure 12-15 shows graphically the amount of movement in each direction as the pendulum swings through one complete cycle of motion. Time is shown on the horizontal axis. Because the complete cycle occurs in one second, the horizontal axis is marked off in hundredths of a second.

The amount of movement of the pendulum in one direction and then the other is shown on the vertical axis. We cannot say that the movement either to the left or to the right is negative. It just doesn't make sense. However, in order to show this movement on the graph, we can mark the vertical axis above the horizontal axis as *right* and below the horizontal axis as *left*.

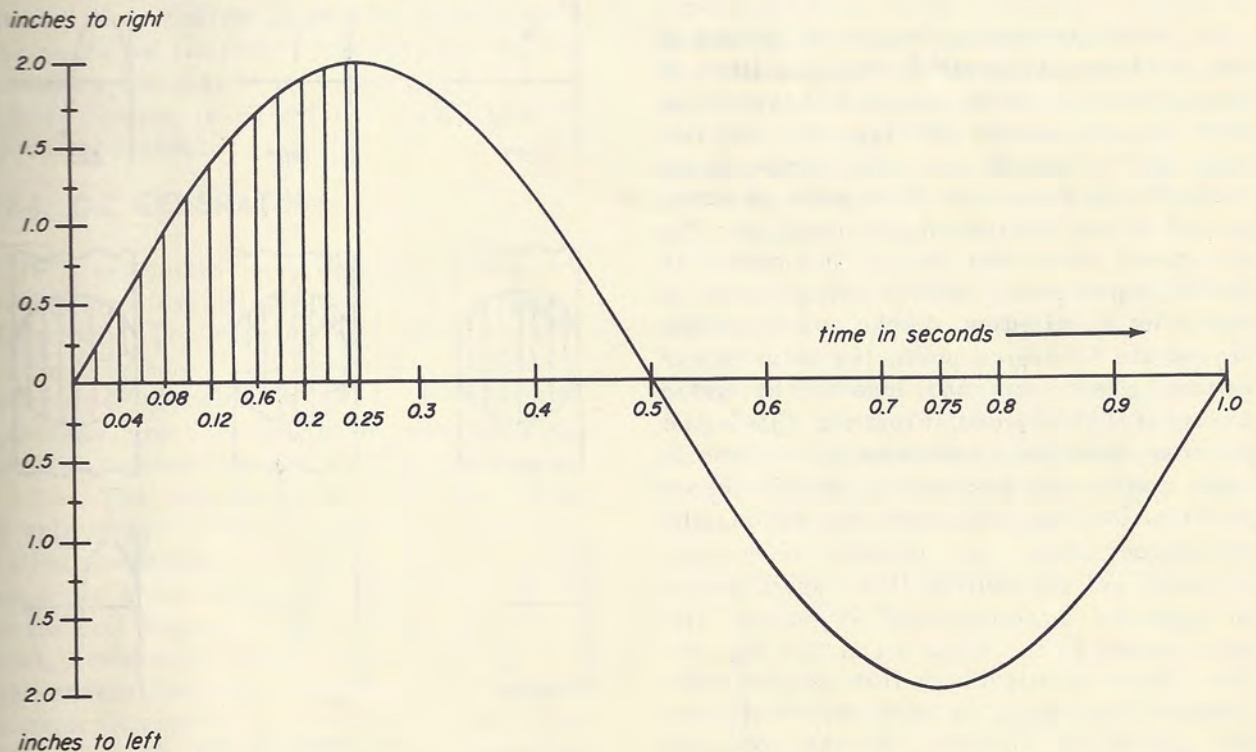


Fig. 12-15

zontal axis as *left*. This is what the draftsman did when he drew the curve of Fig. 12-15.

Looking closely at this curve, you can see that it is possible to determine the amount of movement either to the left or to the right from the zero position at any portion of a second. The vertical lines drawn to the curve from the horizontal axis represent the amount of movement from the zero position at several instants in the first part of the cycle.

The curve of Fig. 12-15 is the same as some of the waveforms that you saw in Theory Lesson One. We call it a *sine curve* or *sine wave*. You will see and use a sine wave many times in this course. It is sometimes used as a symbol for cycles per second. For example, 500 cps can be written 500 ~.

12-5. SIMPLE A-C GENERATOR

The simple generator that you studied earlier in this lesson produces alternating current. To prove this, let us see what happens to the direction of current and the amount of current flow during one rotation of the

coil. Examine Fig. 12-16, which shows a complete rotation of the coil in the magnetic field and the amplitude of voltage for each 45 degrees of rotation. This series of drawings shows only the current flowing in cross section *A* of the coil. This is so that we may follow the changes that take place through one rotation, or one *cycle*, as it is called. Just bear in mind that the direction of the flow of the current at cross section *D* is opposite to the direction of flow at cross section *A*.

Starting with *A*, in zero position, we follow its rotation in nine drawings. The graph below each drawing shows the amplitude of induced voltage and direction of current flow for each 45 degrees of rotation. The horizontal axis is marked off in degrees of rotation. The position on the vertical axis where it meets the horizontal axis represents zero voltage. Any point above the horizontal axis represents an amplitude of voltage of given polarity, and any point below the horizontal axis represents an amplitude of voltage of opposite polarity. In each of these graphs, the position of the black dot shows the direction of the current flow.

In the first drawing, where the motion of the conductor is parallel with the lines of force, the value of the voltage is shown to be zero. In the second drawing, the coil has rotated 45 degrees, and the instantaneous value of the voltage at 45 degrees is represented by the position of the black dot. The next panel shows that the coil has rotated to the 90-degree point, and the voltage value at this point is maximum. As the coil continues beyond the 90-degree point, the value of the voltage grows less and less to the value shown at 135 degrees. From the 135-degree position, the voltage continues to decrease in value until it reaches zero at the 180-degree position. As the coil continues beyond the 180-degree point, the polarity of voltage reverses and the current flows again but in an opposite direction until it reaches the value shown by the black dot at 225 degrees. The current continues to flow in this same direction, increasing in value until it reaches the 270-degree position. As the coil continues to rotate beyond the 270-degree position, the value of current decreases in value until it reaches the amount indicated at the

315-degree position. As the coil completes the first cycle, the current gradually decreases to the zero voltage point at 360 degrees.

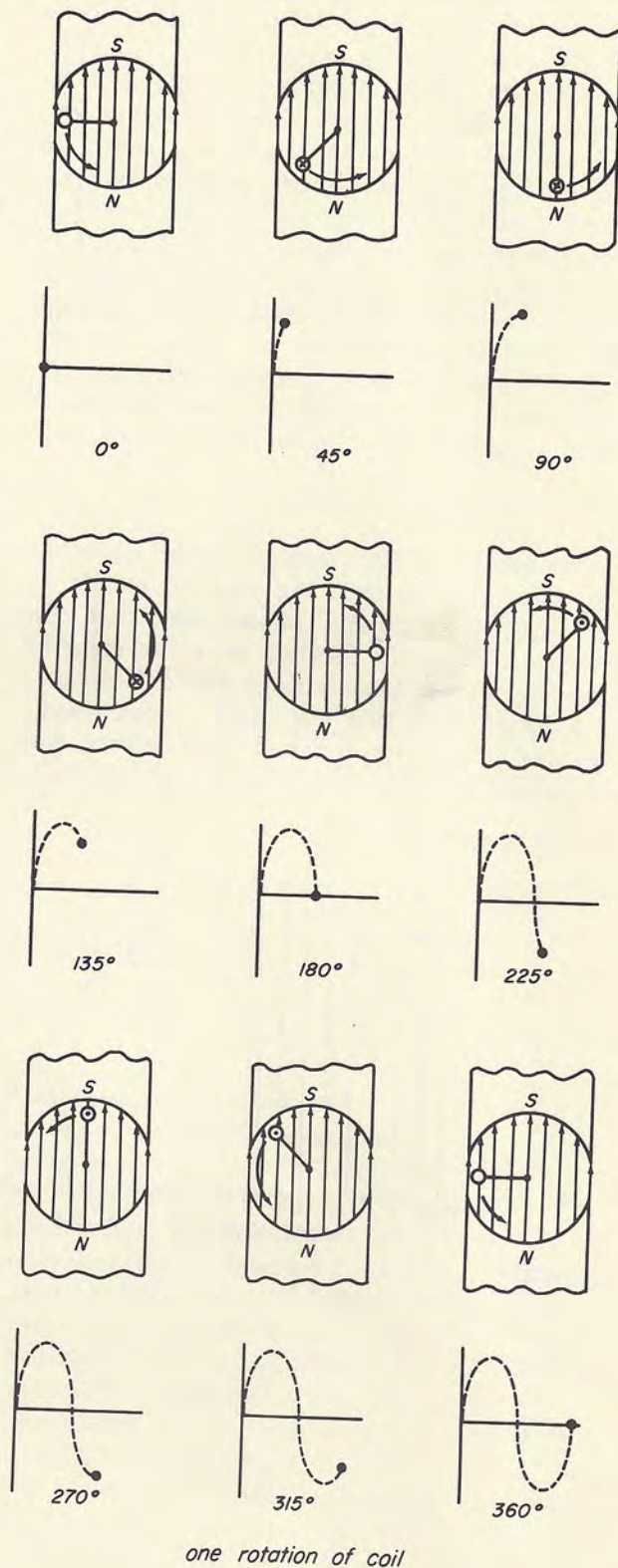


Fig. 12-16

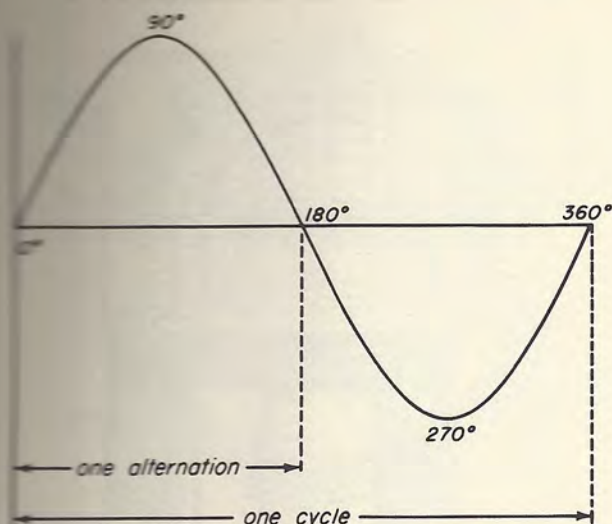


Fig. 12-17

By joining together all of the instantaneous values of voltage obtained in one rotation, or cycle, we produce a sine wave, as shown in Fig. 12-17. Of course, the coil continues rotating; but just so long as the coil moves at the same speed, each rotation will produce the same waveform in the same period of time. All the changes that occur in one direction, either above or below the horizontal axis, during one cycle, make up an *alternation*; there are two alternations to one cycle. The frequency of an alternating current depends upon the number of complete cycles per second. For example, the standard for a-c power, in the United States, is 60 cycles, or 120 alternations per second.

12-6. D-C GENERATORS

D-C generators are very much like a-c generators, except for one very important difference. The rotating coil of a d-c generator terminates in a *commutator* instead of in a pair of collector rings. A single-coil generator, such as we have been studying, uses a commutator like that shown in Fig. 12-18a. The commutator shown is made from a split copper ring. The two split sections, called *segments*, are insulated from each other by a nonconducting material. One end of the coil terminates in one segment, and the other terminates in the other segment. Two carbon brushes make contact with the commutator segments as the coil rotates. For almost a half a rotation, brush A is connected to the number-one segment of the commutator. Then, as the coil continues to rotate, the

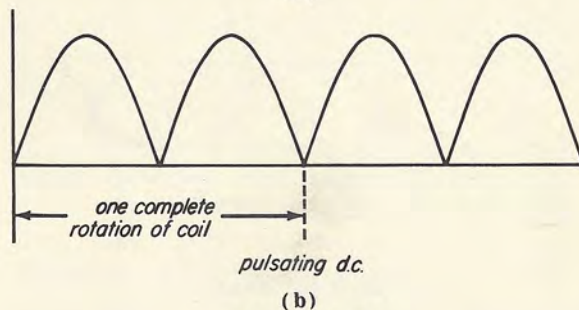
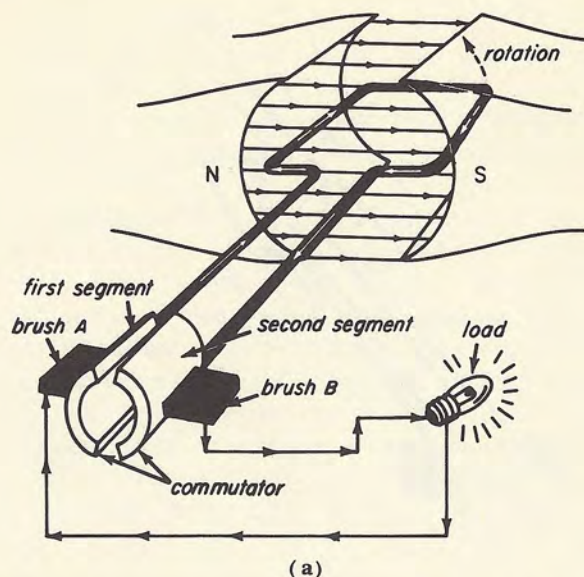


Fig. 12-18

second segment of the commutator comes in contact with brush A. Each half-cycle, the commutator switches the coil connections to the two brushes, so that each brush always receives current in the same direction. The waveform of the current flowing in the outer circuit is as shown in Fig. 12-18b. This is called *pulsating d.c.*

Pulsating d.c., while it rises and falls in value, always flows in the same direction. However, the pulsating d.c. from a single-coil generator doesn't look or act much like the d.c. we get from a battery. The d.c. that we obtain from a battery in good condition has a constant value and can be represented by a straight line, as shown in Fig. 12-19.

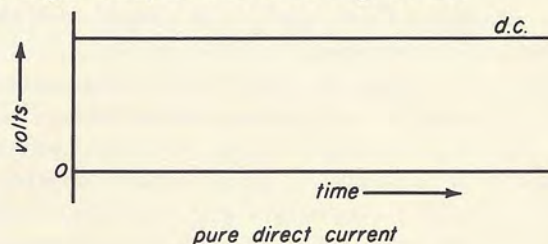
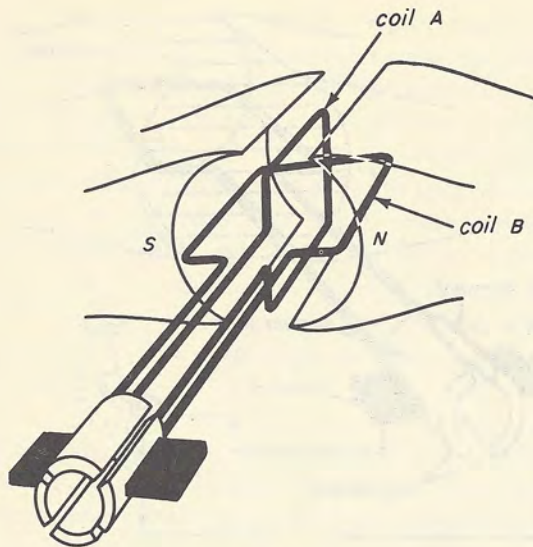
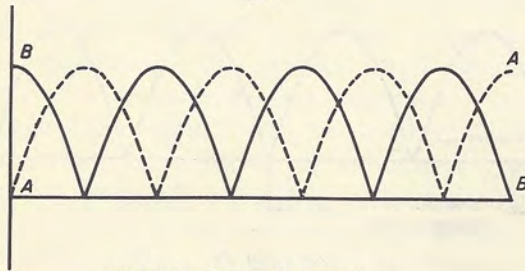


Fig. 12-19

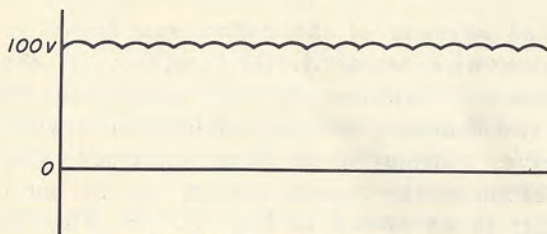


(a)



output of 2-coil armature

(b)

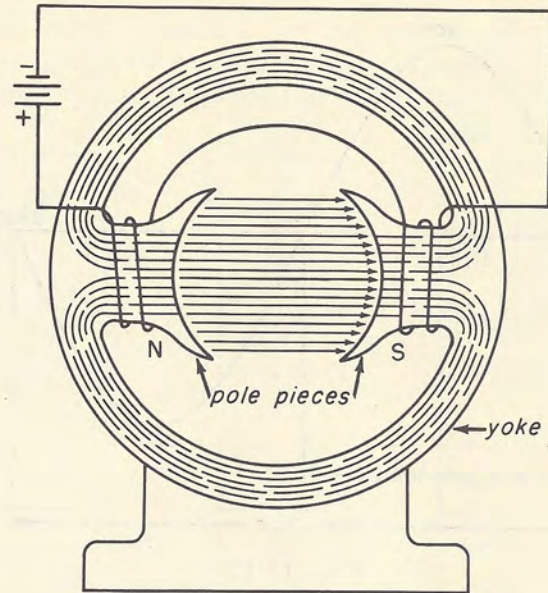


direct current with a ripple

(c)

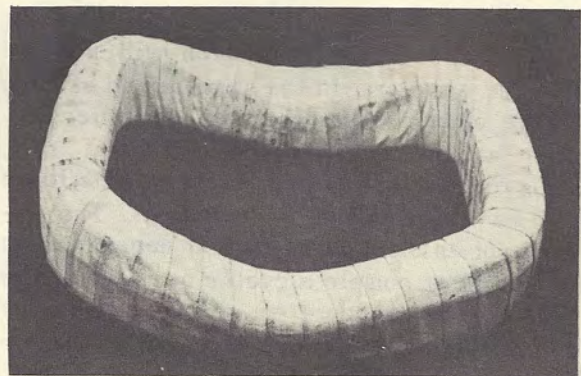
Fig. 12-20

The ideal d-c generator is one that produces d.c. of a constant value, such as that shown in Fig. 12-19. However, such a generator does not exist among the electromagnetic types. However, we can improve the output waveform by increasing the number of armature coils. For example, if two coils are placed at right angles to each other, as shown in Fig. 12-20a, and the armature is allowed to rotate, when coil A is in the zero-voltage position, coil B is in the maximum-voltage position. Later, when coil B reaches zero-voltage position, coil A is in maximum-voltage position. Each coil has two ends, so a two-coil d-c generator requires a four-section commutator. As you



separately excited generator field

(a)



(b)

Fig. 12-21

can see in Fig. 12-20b, the waveform of coil A is maximum when wave B is minimum, and wave B is maximum when wave A is minimum. Thus, the voltage does not fall to zero. To improve the waveform still further, we can add more coils. The more coils that we use in the armature, the less is the variation in the output waveform. Thus, from a practical d-c generator, we may get a waveform like that of Fig. 12-20c. This is no longer a pulsating d.c. We say that it is a d.c. with a ripple. The ripple is the small variation that still remains in the waveform.

12-7. PRACTICAL GENERATORS

In our discussion of generators and generator action, we have assumed that the

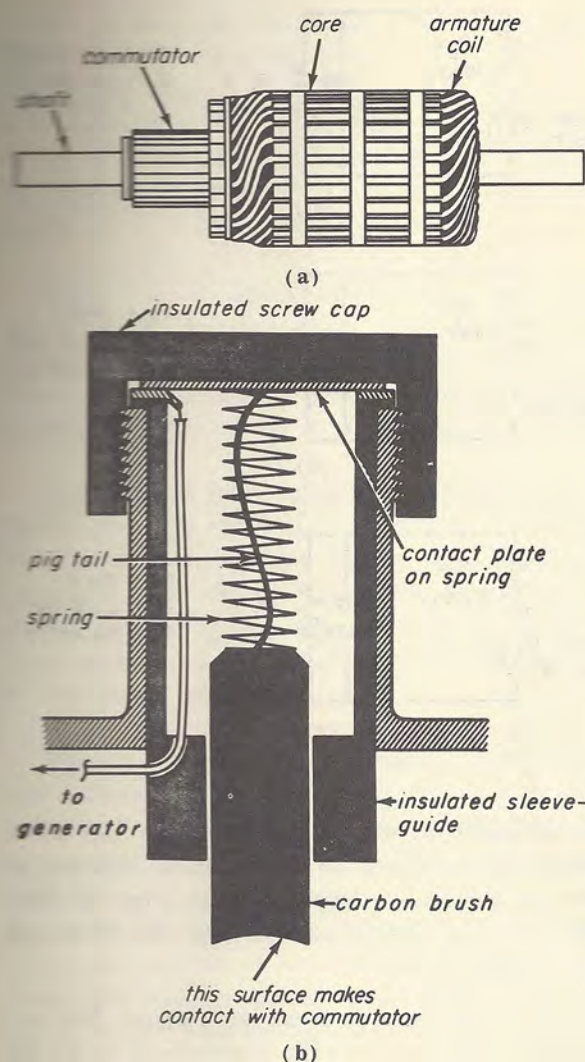


Fig. 12-22

source of flux was a permanent magnet. Most generators do not use a permanent magnet to produce the magnetic field. Instead, electromagnets are used. Figure 12-21a shows a generator frame, called a *yoke*, with electromagnets mounted in place. The drawing shows only a couple of turns of wire wound around each pole piece. The actual *field coils* (as they are called) of a practical generator contain either many turns of heavy-duty wire or a much greater number of turns of finer wire. The field coils are wrapped with insulating tape and look like those shown in Fig. 12-21b.

The source of voltage for the field coils is shown as a battery. We say of such a field that it is *separately excited*. A-C generators require separate excitations because they deliver only a.c. If a.c. were to be fed to the field coils, the polarity of the field would

change constantly. This is undesirable. We want only the rotation of the armature to cause alternations of the output. So a source of d.c. usually a separate d-c generator, is used to excite the field of a-c generators.

In d-c generators, on the other hand, field excitation is generally provided by feeding back into the field coils a portion of the emf produced by the generator. This is called *self-excitation*. In such cases, the excitation of the generator field, when first starting, may be obtained from the residual magnetism that exists in the core of the electromagnetic field coil. In cases where there is not sufficient magnetism in the core, as when the generator is placed in service for the first time, or has not been in use for a long period of time, it is necessary to provide excitation from a battery or other d-c source when the generator is first started.

Up until now we have studied only simple coils, rotating in a magnetic field. Figure 12-22a shows the *armature* of a d-c generator. The armature is the name of the complete assembly. It includes the shaft, the armature coil, the core material, and the commutator. Figure 12-22b shows a carbon brush and its mounting, such as is used in making contact with a rotating commutator.

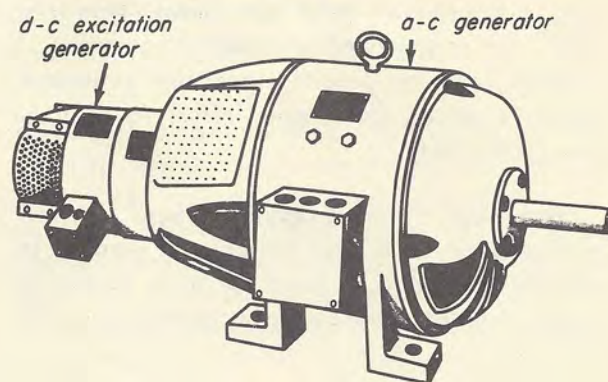


Fig. 12-23

In low-power a-c generators, the a.c. induced in the armature coil may be taken from the collector rings by brushes. However, in high-power commercial a-c generators, the amount of current passing through the brushes would be excessive. For this reason, heavy duty a-c generators use stationary armature coils, and the electromagnetic fields rotate, with brushes supplying the field excitation. Figure 12-23 shows an alternating current generator with a

rotating field excited by a small d-c generator mounted next to it.

Internal Resistance. In our study of primary and secondary cells, we found that some of the emf produced by chemical action was lost because of internal resistance. For the same reason, the terminal voltage of any generator of the type we have studied in this lesson will be less than the induced emf. The internal resistance of such generators causes a voltage drop inside the generator whenever a load is applied to its terminals. The internal resistance of a generator is caused by the resistance of the armature coil, the resistance of brushes, and, in a self-excited generator, by the resistance of the field coil.

Loads. When you think of a generator or of generator action, remember that a generator changes one form of energy into another form of energy. We put in mechanical energy and out comes electrical energy. This means, therefore, that it takes work to make a generator produce electricity, and the greater the load on the generator, the greater is the effort required to operate it. For example, the armed services use a combination radio receiver and transmitter, powered by a hand generator. When the receiver section is operating, there is very little load on the generator, and it is easy to turn the generator shaft. However, when the transmitter section is operating, a greater load is placed upon the generator, and it requires much more effort to turn the generator shaft.

Maximum Power Transfer. When a generator is used to deliver power to a load, it is usually desirable to have as much power as possible transferred from the generator to the load.

It is not possible to get all of the generated power into the load, because some of it is used up in the internal resistance of the generator. Let us see how maximum power transfer can be obtained.

You know that any source of electrical power, whether it is a battery or a generator, has internal resistance. Let us consider a generator with an internal resistance of 1,000 ohms, as shown in Fig. 12-24. We will place

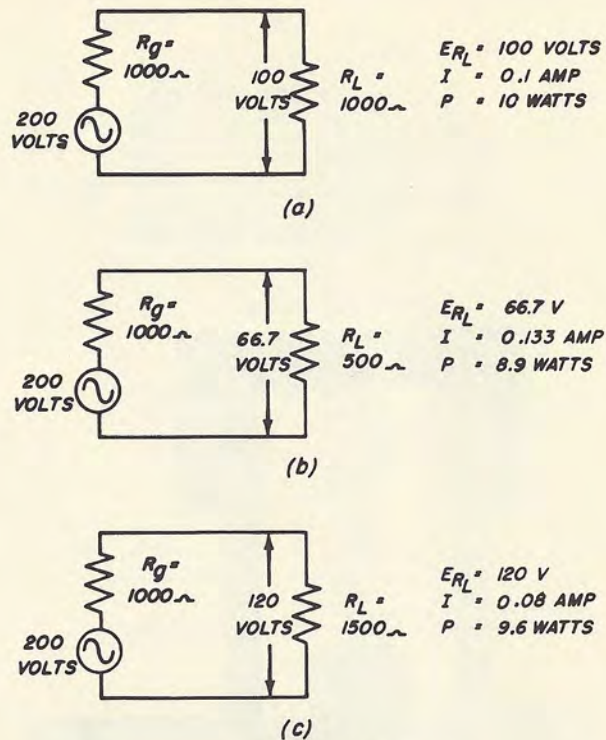


Fig. 12-24

three loads across this generator. The first load will be equal to the internal resistance of the generator, as shown in Fig. 12-24a. We can use Ohm's Law to see the effect of this load.

In effect, this is a series circuit. The resistance of the load is considered to be in series with the internal resistance of the generator. The voltage across these two resistors in series is the 200 volts supplied by the generator. You probably can see at once that, since the two series resistors are equal, the voltage drop across each one is half the total applied voltage, or 100 volts. You can find the current across the load resistor R_L by Ohm's Law:

$$I = \frac{100}{1,000} = 0.1 \text{ amp}$$

To find the power delivered to the load, you use the following power formula:

$$P = EI$$

Therefore, the power delivered to the load is:

$$\begin{aligned} P &= E_{RL} I_{RL} \\ &= 100 \times 0.1 \\ &= 10 \text{ watts} \end{aligned}$$

If the load on the same generator is reduced to 500 ohms, as shown in Fig. 12-24b, the power delivered to the load will be only 8.9 watts. You can prove this by performing the same type of calculation that was used for finding the power delivered to a 1,000-ohm load.

Likewise, if you calculate the effect of placing a 1,500-ohm load across the same generator in place of the 1,000-ohm load, as shown in Fig. 12-24c, you will find that the power delivered to the load is only 9.6 watts.

Although we have made only three calculations, you will find, if you wish to try other values of load, that no matter what load resistance you choose, maximum transfer of power occurs when the resistance of the load is the same as the internal resistance of the power source.

You will learn in later lessons that tubes and antennas are also considered to be power sources, and that the load resistance has to be matched to the resistance of the source for maximum transfer of power. Right now, remember this important rule: *For the most efficient transfer of power from a source to a load, the resistance of the load should be equal to the internal resistance of the power source.*

12-8. TRANSFORMERS

In the early days of commercial electric-power generators, the voltage supplied to homes, offices, and factories was d.c. Today, however, most of the commercially produced electrical power is a.c. There is good reason for this. When d-c power is supplied to a home or other building far from the generating plant, so much voltage may be lost in the power lines (due to resistance) that the voltage available at the receiving end may be too low to operate electrical equipment satisfactorily. So, unless the d-c power source is nearby, it is difficult to obtain electric power at a useful voltage. The voltage of a.c. power, on the other hand, may be raised or lowered to any useful value by means of a *transformer*.

A transformer is a device, without moving

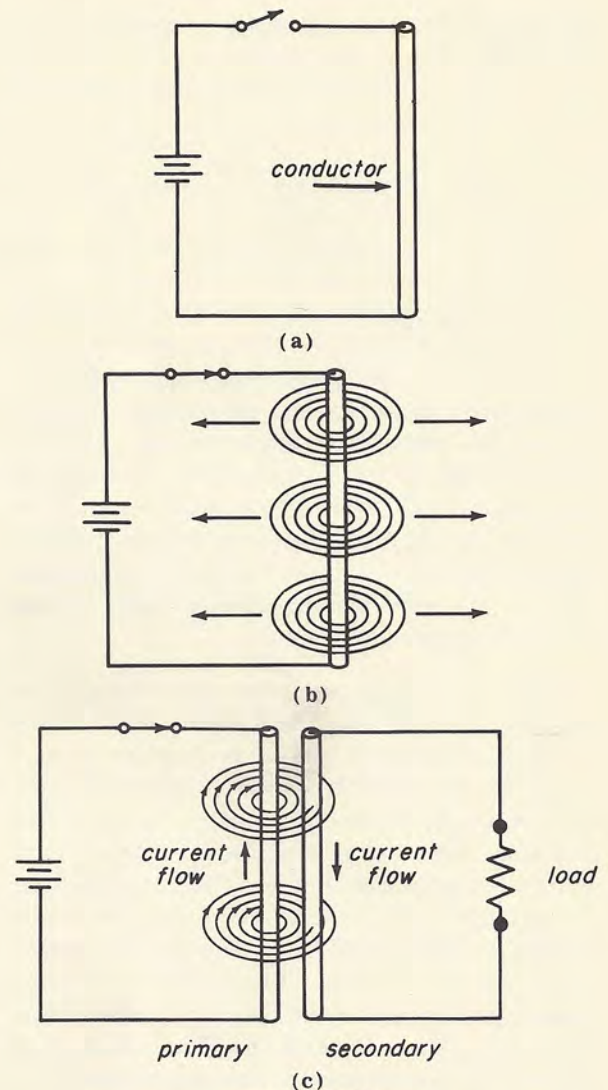


Fig. 12-25

parts, that transfers electricity from one circuit, called the *primary*, to another circuit, called the *secondary*, by means of electromagnetic induction. Many kinds and sizes of transformers are used in radio and television receivers. Some transformers are used to raise a voltage from one value to another. Such transformers are called *step-up* transformers. Other transformers are used to lower a voltage to some needed value. These are called *step-down* transformers. Transformers are so widely used that it pays to know how they work.

While transformers normally operate on alternating current, we will start our study of transformer action by considering what happens when d.c. is applied to a conductor. Figure 12-25a shows a conductor connected in series with a switch (in the open position). This circuit is connected to a battery. From your study of electromagnetism, you know that

when the switch is closed, a magnetic field will form around the conductor, as shown in Fig. 12-25b. You know, too, that the field grows and the flux moves out from the conductor, as shown by the small arrows, until the current reaches its maximum value. If another conductor is placed close to the first conductor as shown in Fig. 12-25c, the flux moving out to form the field will cut the turns of this second conductor. When this happens, a voltage is induced in the second conductor while the field is being formed. If a load is placed across the second conductor, or if the circuit is otherwise completed, the induced voltage will cause a current to flow in the conductor until the field stops growing. Note that the direction of the current that flows in the secondary, as the result of the induced emf, is opposite in direction to the current flow in the primary circuit.

When d.c. is applied to the primary, the induced voltage and the current flow in the secondary last for only the instant that it takes for the current in the primary to reach its maximum value. From then on, the flux lines are stationary, and there is no relative motion between the flux and the secondary, so no voltage is induced. When the switch is opened, the field collapses and the flux moves back into the primary, which causes another instantaneous voltage to be induced and current to flow in the secondary. The direction of secondary current flow is then opposite to the direction of the secondary current when the field was forming.

A single conductor does not have as strong a field as does a coil. In order to increase the flux (and the induced emf), we can use a pair of coils, as in Fig. 12-26. The number of flux lines formed in this transformer depends on the number of turns in the primary and the amount of current flowing in the primary winding.

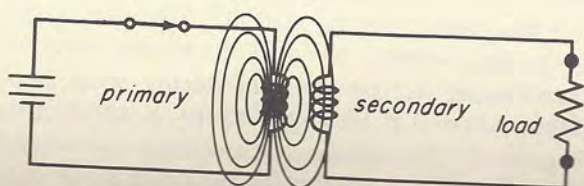


Fig. 12-26

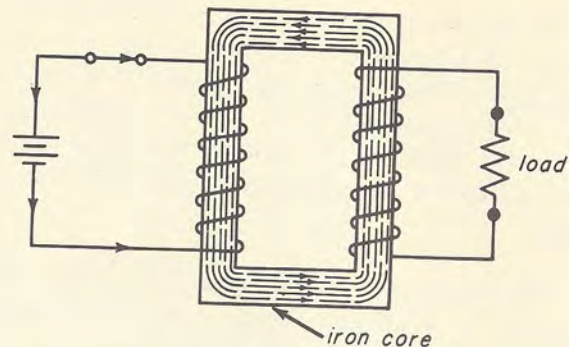


Fig. 12-27

Leakage Flux. Look at Fig. 12-26. Notice that only part of the flux lines actually cut the secondary. As a result, the greater number of flux lines are wasted because they do not contribute to the induction of voltage in the secondary. We call this *leakage flux*. In order to reduce the amount of leakage flux to a minimum, some transformers are wound on iron cores, as shown in Fig. 12-27. When this is done, practically all of the flux lines formed by current flowing in the primary cut the turns of the secondary. As a result, there is little or no leakage flux.

Practical Transformer Action. Pure d.c. applied to the primary of a transformer produces only a momentary current flow in the loaded secondary. Then, until the primary circuit is opened, no further change occurs in the secondary. The current flowing in the primary then produces only heat, which, if the d-c voltage is great enough, may cause the insulation on the primary to burn, and may even cause the wire of the primary to melt. It is possible to apply an interrupted d.c. to the primary to induce an a-c voltage in the secondary. You will learn how this may be done when you study vibrators and auto-radio power supplies. Most practical transformers operate on a.c.

Suppose that 60-cycle a.c. is applied to the primary of a transformer, as in Fig. 12-28. Then, with every alternation, the current flowing in the primary will rise and fall and cause the magnetic field to expand and contract. With 60-cycle current, this happens 120 times a second, as the primary current changes direction twice in each cycle. The emf induced in the secondary causes the secondary current to change direction at the same rate. It has the same frequency as the primary

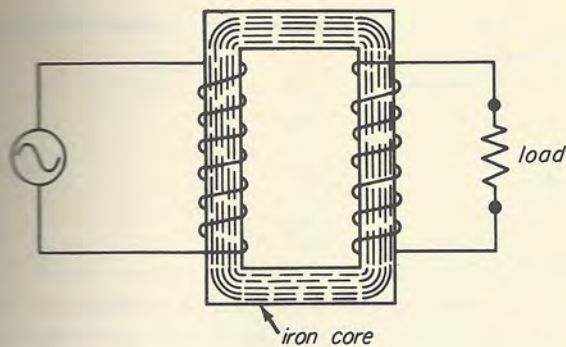


Fig. 12-28

voltage. The voltage induced in the secondary rises and falls as the voltage applied to the primary rises and falls. The only difference between the two voltages is that they are always opposite in polarity, and the currents that flow in each winding are opposite in direction. However, if the winding direction of the secondary is reversed, current direction and voltage polarity become the same as the primary.

Turns, Voltage, and Current Ratios. The amount of voltage induced in the secondary of a transformer depends on the number of turns in the secondary winding and the number of flux lines that cut the secondary turns. The number of flux lines that cut the secondary depend on the number of turns in the primary and the voltage across it. So, we find that there is a fixed relationship between primary and secondary turns and between the primary voltage and the secondary voltage. For example, if the secondary has twice the number that the primary has, then the secondary voltage will be twice that of the primary. Or, if the secondary has half the number of turns of the primary, the secondary voltage will be half that of the primary. So we can say that *the ratio of the secondary turns to the primary turns is equal to the ratio of the secondary voltage to the primary voltage*. In formula form it looks like this:

$$\frac{\text{Number of secondary turns}}{\text{Number of primary turns}} = \frac{\text{Secondary voltage}}{\text{Primary voltage}}$$

$$\text{or simply, } \frac{N_s}{N_p} = \frac{E_s}{E_p}$$

Let's see how these ratios may be used. For example, suppose that a supply voltage is 115 volts, and the primary winding has

1,150 turns. If we want a secondary voltage of 345 volts, how many turns must the secondary have?

$$\begin{aligned} N_s &= \frac{E_s}{E_p} \times N_p \\ &= \frac{345}{115} \times 1,150 \\ &= 3 \times 1,150 \\ &= 3450 \text{ turns} \end{aligned}$$

This formula also may be used to find the voltage induced in the secondary when you know the number of turns and the voltage of the primary and the number of turns in the secondary. For example, how much voltage is induced in the secondary when the primary turns are 1,170, the secondary turns are 63, and the primary voltage is 117 volts?

$$\begin{aligned} E_s &= \frac{N_s}{N_p} \times E_p \\ &= \frac{63}{1,170} \times 117 \\ &= \frac{63}{10} \\ &= 6.3 \text{ volts} \end{aligned}$$

Of course a transformer does not generate electricity—it only transfers it from one circuit to another. In the transfer, the voltage induced in the secondary may be more or less than the voltage in the primary, depending on the turns ratio. While we may raise or lower voltages by using step-up or step-down transformers, we cannot get any more power out of the secondary than that in the primary. In fact, to be accurate, we don't get as much power from the secondary as that in the primary. Later in this lesson you'll learn why this is so. Right now, because well-designed transformers are very nearly 100-percent efficient, we will assume that we get as much power out of a transformer as we put into it. The very slight error that will result is unimportant. So we can say that the primary power equals the secondary power, or

$$P_p = P_s$$

The primary power is equal to the voltage in the primary multiplied by the current flow-

ing in the primary, and the secondary power is equal to the voltage induced in the secondary multiplied by the current that flows in the secondary. So, if

$$P_p = E_p \times I_p$$

$$\text{and } P_s = E_s \times I_s$$

$$\text{then } E_p \times I_p = E_s \times I_s$$

Let's see how this works out in a practical transformer. Suppose we have a step-up transformer. The primary voltage is 117 volts, the secondary voltage is 350 volts, and the load on the secondary draws 100 ma. How much current flows in the primary (assuming the transformer to be 100-percent efficient)?

$$E_p \times I_p = E_s \times I_s$$

Substituting figures, we get:

$$117 \times I_p = 350 \times 0.1$$

$$117 \times I_p = 35$$

$$\text{then } I_p = \frac{35}{117}$$

$$= 0.3 \text{ amp or } 300 \text{ ma}$$

Let's take another example. Suppose this time we have a step-down transformer. The primary is connected to 110 volts, and the secondary draws 2 amperes at 6.3 volts. What is the primary current?

$$E_p \times I_p = E_s \times I_s$$

$$110 \times I_p = 6.3 \times 2$$

$$110 \times I_p = 12.6$$

$$I_p = \frac{12.6}{110}$$

$$= 0.114 \text{ amp or } 114 \text{ ma}$$

From these examples, you can see that if the secondary voltage is *higher* than the primary voltage, the secondary current is *lower* than the primary current. Likewise, if the secondary voltage is *lower* than the primary voltage, the secondary current is *higher* than that flowing in the primary. We say that the current ratio is an inverse ratio to the turns

or voltage ratios. Written as a formula, this becomes:

$$\frac{N_s}{N_p} = \frac{I_p}{I_s}$$

or

$$\frac{E_s}{E_p} = \frac{I_p}{I_s}$$

One very important point to remember is that the current flowing in the primary winding depends upon the current flowing in the secondary. Of course, the current flowing in the secondary depends upon the load connected to the secondary. If there is no load on the secondary (if the secondary is open), the current flowing in the primary is very small and is called the *magnetizing current*.

12-9. TRANSFORMER LOSSES

As we have said, transformers are not really 100-percent efficient; there is always some loss in power, however small it is. In designing a transformer, the manufacturer considers all the things that cause a transformer to lose power and tries to overcome them. Most transformers are better than 90-percent efficient, and first-grade transformers are better than 98-percent efficient.

Copper Losses. One form of power loss in a transformer is due to the resistance of the primary and secondary windings. Such losses are called *copper losses*. Resistance in any conductor produces heat, which, because we don't want to produce heat, must be considered a loss. Copper losses may be reduced by winding a transformer with low-resistance large-diameter wire. However, such a transformer is likely to be large and heavy. If weight and space are important in planning a piece of equipment, it may be necessary to compromise and choose wire that has a reasonable amount of resistance so that the transformer will fit where we want it to.

Flux Losses. Earlier in this lesson, you learned that some of the flux lines formed by the primary do not cut the turns of the secondary. We call this *leakage flux*. Wherever there is leakage flux, we have a power loss. You learned, too, that we can reduce leakage

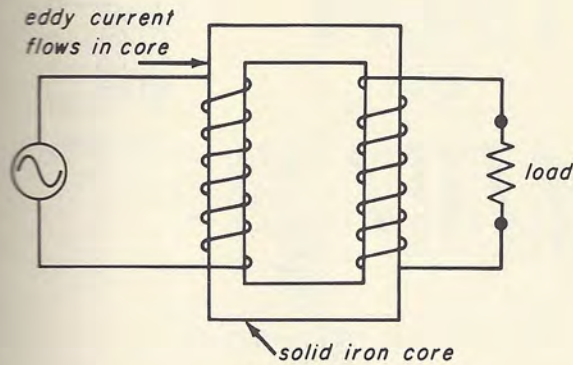


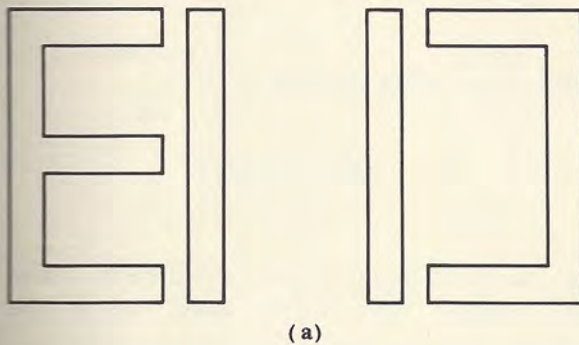
Fig. 12-29

flux by using iron cores. However the use of these cores presents us with another problem.

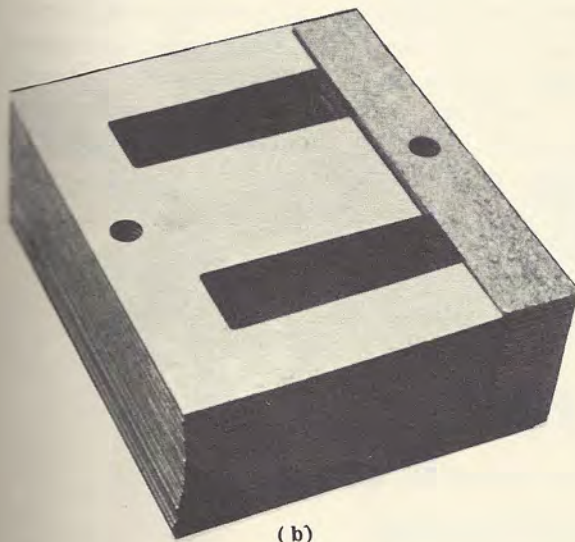
Eddy Currents. Any metal that moves in a magnetic field or through which a magnetic field moves has an emf induced in it. Whenever a current flows in a metal that is not part of any transformer winding, we call it an *eddy current*. When a solid iron core is used, as in Fig. 12-29, an emf is induced in the core, which causes a current to flow in the

ring of the core. Such a current serves no useful purpose, so we call it an eddy-current loss. We can reduce the amount of power lost in eddy currents by using cores made from thin sheets (called *laminations*) of silicon steel. These laminations are usually 0.01 to 0.03 thick and are often shaped like those shown in Fig. 12-30a. The cores of most transformers are constructed of E and I laminations. Others may be constructed of C and I laminations or other shapes. A typical commercial transformer, the core of which is assembled of E and I laminations, is shown in Fig. 12-30b. The laminations may have an oxide coating, a coating of varnish, or some other insulation. Assembled in this way, the core provides a very poor path in which current may flow, and, as a result, there is very little eddy-current loss.

Hysteresis Loss. Still another kind of power loss in a transformer is caused by the change in magnetic polarity that takes place in the core twice in every cycle. It is called *hysteresis* and, at times, *magnetic friction*. It causes the core to heat up and represents a loss of power. It takes energy to magnetize the core first in one direction and then in the other. The amount of energy needed to shift the molecules with each alternation in the primary current varies with the material used in forming the core. For example, a core made from silicon steel has about $1/25$ the hysteresis loss of cast iron and less than $1/6$ the loss of common sheet steel. You can see why silicon-steel laminations are so widely used in making transformer cores.



(a)



(b)

Fig. 12-30

12-10. TRANSFORMER TYPES

Transformers of many types are used in radio and television receivers. Some of these are shown in Fig. 12-31. High frequency transformers, such as those used in radio-frequency circuits, sometimes have either air cores or powdered-iron cores. (Iron core is the name usually given to a core made from any of the magnetic materials.)

Transformers may have tapped primaries or secondaries, as shown by the schematic

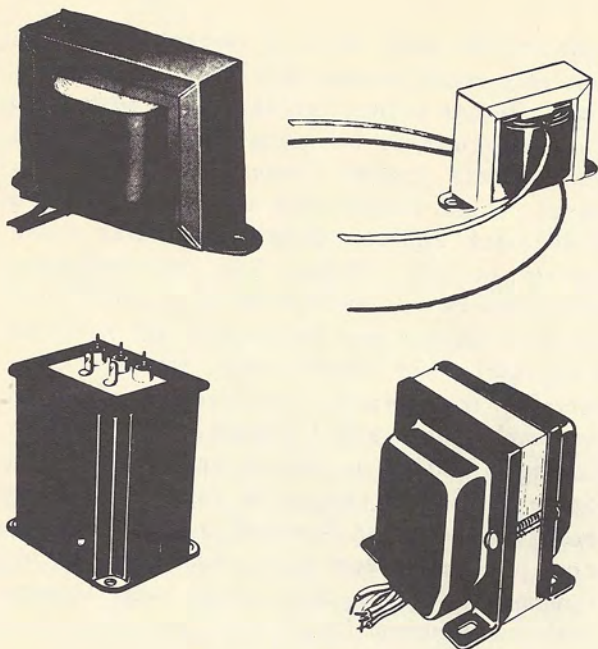


Fig. 12-31

symbols in Fig. 12-32a. Power transformers may have two or more secondaries, as shown in Fig. 12-32b. The transformer shown has one step-up secondary and two step-down secondaries. (To determine the amount of power in the primary, it is necessary to find the total power of all the secondaries, which will be slightly less than the primary power.)

Auto-Transformers. It is not necessary that the primary winding and the secondary be separate. In one type of transformer, called the *auto-transformer*, the primary may be part of the secondary, in a step-up transformer (shown in Fig. 12-33a), or, in a step-down transformer, the secondary may be part of the primary, as shown in Fig. 12-33b. The turns ratio of an auto-transformer is equal to the voltage ratio (as in standard transformers)

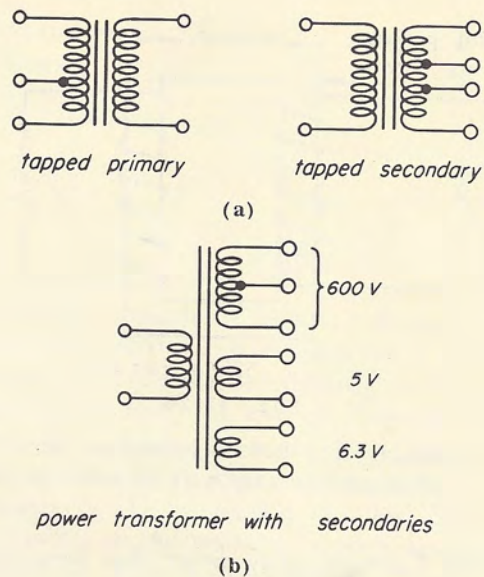


Fig. 12-32

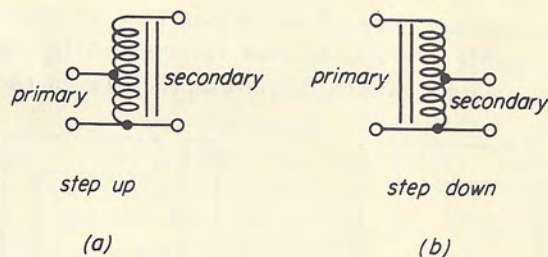


Fig. 12-33

and inversely equal to the current ratio. Auto-transformers are seldom used where the voltage ratio is very high. Because the primary and secondary are not separate windings, it is sometimes dangerous to connect certain types of line-powered test equipment to receivers powered by auto-transformers. However, very few receivers are powered by such transformers.